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A review of crack closure measurement by compliance technique and the normalized-extended ASTM method as a currently most refined, practical and simple one

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Abstract

The intrinsic drawbacks of the standard ASTM compliance offset method for determination of crack opening load is described and the normalized-extended ASTM method as an alternative is introduced and applied to random loading tests on 7475-T7351 aluminum alloy. Fatigue crack growth under random loading is successfully predicted by the effective stress intensity factor range based on the crack opening load determined by the normalized-extended ASTM method. Conclusively, it is strongly recommended to use the normalized-extended ASTM method. It is also found that the crack closure behavior of 7475-T7351 aluminum alloy under random loading is significantly different from that of 2024-T351.

Keywords: Crack closure; Crack opening load determination; Standard ASTM 2% offset method; Normalized-extended ASTM offset method; random loading; 7475-T7351 aluminum alloy

1. Introduction

Although negative arguments currently exist, it is undeniable that the crack closure concept is indispensable for better understanding and assessing of fatigue crack growth behaviour, in spite of its inherent limitation. In utilizing the concept, the most important is to precisely measure the crack closure behaviour and to determine the crack opening load accurately and consistently. Over more than 30 years, the authors' group have investigated the crack closure phenomenon and developed or proposed several methods to try to measure and determine the crack opening load as accurately and consistently as possible. Most recently, the authors [1] have proposed a new, modified ASTM offset method called "the normalized-extended ASTM method," based on the extensive re-examination of the original ASTM 2% offset method [2]. The normalized-extended ASTM method may be considered as a currently most refined, practical and simple crack opening determination method. In this paper, the new method is outlined,

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along with reviewing crack closure measurements by the compliance technique and its application to random loading is described.

2. Compliance technique

The compliance technique has been most widely used for crack closure measurement, due mainly to its experimental simplicity, and there are two main methods for determination of the crack opening load P_{op} using the compliance technique

: As shown in Fig. 1, one is the conventional method utilizing the load-displacement (P-δ) curve as originally used by Elber [3] and the other is the unloading elastic compliance method utilizing the load-differential displacement (P-Δδ) curve, which was first proposed by Kikukawa et al. [4]. As shown in Fig. 2, even when crack closure is hardly found in the P-δ curve, the P-Δδ curve method can detect the crack closure definitely. The principal characteristics of two methods may be summarized in Table 1.

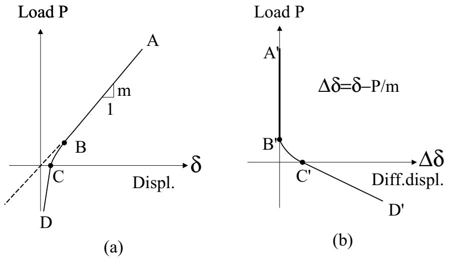


Fig. 1 Compliance technique (a) conventional; (b) unloading elastic compliance

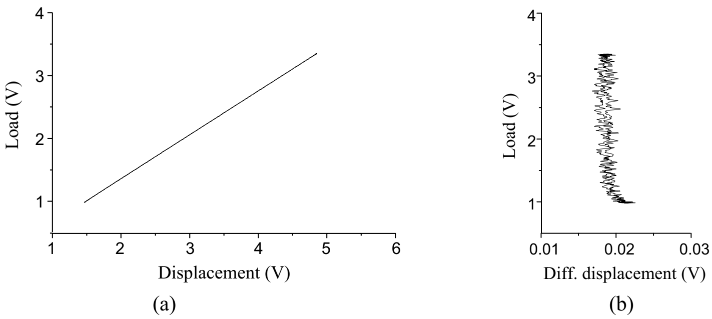


Fig. 2 Crack closure measurements (a) by conventional method; (b) by unloading elastic compliance method

As it can measure crack closure with high sensitivity and also measure the crack length simultaneously, the unloading elastic compliance (P-Δδ curve) method has been successfully applied to investigate a wide range of fatigue crack growth issues including crack growth behaviour under variable amplitude and random loading and growth behaviour of small cracks and surface cracks, particularly by Kikukawa and Jono's group [5, 6] and Song's group [7-9]. However, the method has some drawbacks: First, its measurement procedure is slightly complicated. Second, the crack opening load is usually determined visually with the naked eye of the observer and consequently, is likely to depend on the observer's experience. Probably, it is these drawbacks why the P-Δδ curve method could not become more popular despite of its inherent merits above mentioned. On the other hand, the conventional P-δ curve method has become the ASTM standard method, by employing the linear fitting and offset compliance approach. The ASTM method is very simple to apply, but the method also has some serious intrinsic drawbacks and in fact, has not been used so widely and effectively as has been expected. However, it is worthy of note that its procedural simplicity is the most appealing merit of the ASTM method.

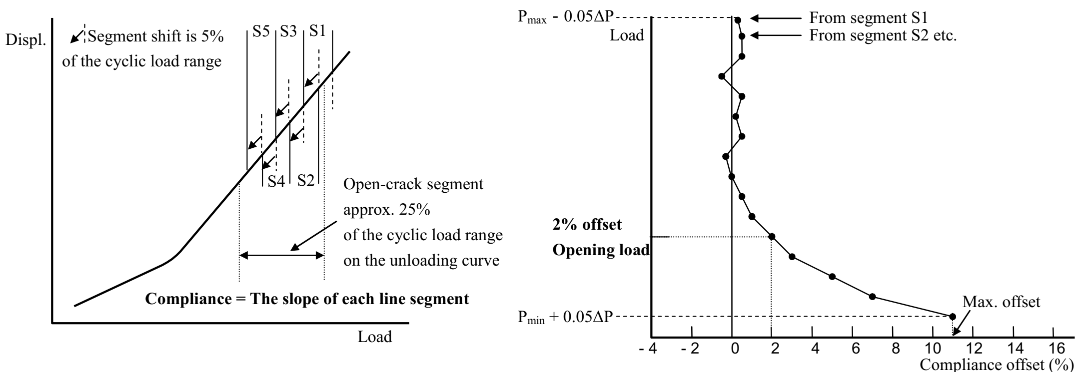
Table 1 Principal characteristics of the conventional and unloading elastic compliance methods

Measurement		Conventional (P-δ curve)	Unloading elastic (P-Δδ curve)
Procedure	Easiness to apply	Easy	Slightly complicated
	Sensitivity	Low	High
	Resolution	Low	High
Crack closure	Noise-	Insensitive	Sensitive
	Standardization	Established	No
	Well-used method	ASTM offset	Visual
	Automatization	Easy	Not so easy
	Sensitivity	Low	High
Crack length	Resolution	Low	High
	Automatization	Not easy	Easy

3. The ASTM offset method [2] and its intrinsic drawbacks

Only the outline of ASTM method is here described. Digitized load-displacement data are collected for a complete load cycle. Referring to Fig. 3a, on the unloading curve, a least squares straight line is fitted to the upper segment of the curve that spans a range of approximately 25% of the cyclic load range. The slope of this line is assumed to be the compliance value that corresponds to the fully open crack configuration. Next, on the loading part of a load–displacement curve, least-squares straight lines are fitted to segments of curve that span a range of approximately 10% of the cycle load range and that overlap each other by approximately 5% of the cyclic load range. The compliance offset is calculated by comparing the compliance of each segment with the open-crack compliance.

$$\text{Compliance offset}(\%)=\frac{[(\text{open-crack compliance})-(\text{compliance})]}{(\text{open-crack compliance})}\times 100 \quad (1)$$



(a) (b)

Fig. 3 Determination of opening load due to ASTM offset method

The (compliance offset, mean load) points from segments are plotted and connected with straight lines as shown in Fig. 3b. The opening load corresponding to the selected offset criterion (1, 2, or 4%) is determined as the lowest load at which a line connecting points has the value of compliance offset equal to the offset criterion. The 2% offset criterion is typically used and is considered to provide practically good results. The ASTM offset method has been examined widely so far by many researchers [10-14] and particularly in previous work [1], the authors re-examined it in more detail and more thoroughly, through simulation study. The problems with the ASTM method can be summarized into the following two issues.

3.1 Discontinuity of opening load values

As can be easily found in Fig. 3b, the ASTM method can provide opening load values only for the load range between (P_{max} – 0.05ΔP) and (P_{min}+0.05ΔP), because the compliance offset is plotted against the mean load of the segment span of 10% of the cyclic load range. A serious problem is the lack of opening load value between (P_{min}+ 0.05ΔP) and P_{min}. The ASTM method provides only two values, (P_{min}+ 0.05ΔP) or P_{min} as the minimum value of the opening load. It results in the jumping behavior in the opening load data (the P_{op} – K_{max} plots) and consequently, also in the da/dN - ΔK_{eff} plots as an example is shown in Fig. 4. In particular, the jumping behavior may lead to large data scatter in the da/dN - ΔK_{eff} relationship, which deteriorates the ASTM method.

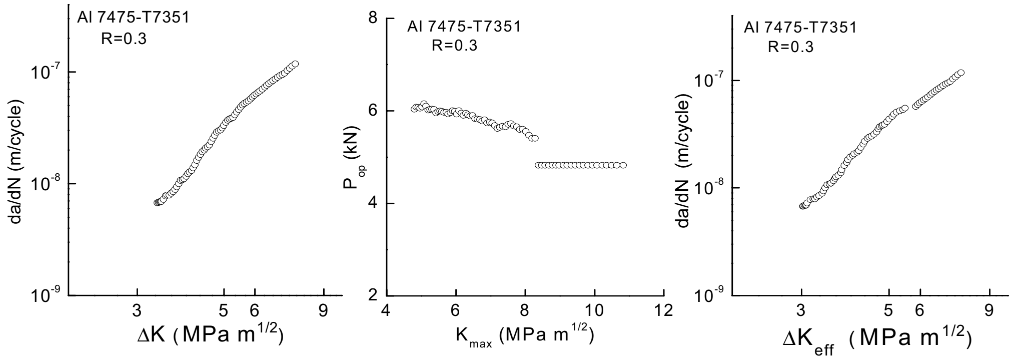


Fig. 4 Discontinuity problem with the ASTM method

3.2 Dependence of opening load on the maximum compliance offset value

Simulation studies based on the ideal, noiseless load-displacement curves with predetermined opening load have shown that the ASTM method the opening load when the maximum compliance offset is relatively small, and estimates accurately, or overestimates the opening load as the maximum compliance offset increases. The value of the maximum compliance offset at which the ASTM method provides accurate opening load varies, depending on the stress ratio R. Conclusively, the ASTM method is very likely to provide inconsistent opening load results, depending on the maximum compliance offset value and the stress ratio. This drawback is referred to as ‘inconsistency problem’.

4. Refinement of the ASTM method through modifications

As the ASTM method, although has some serious drawbacks, is well established and its procedural simplicity is very appealing, it may be practically good policy to refine the ASTM method by solving the related two problems referred to in the preceding section.

4.1 Extended ASTM method to solve the discontinuity problem

As the discontinuity problem described in the subsection *3.1* is due to the segment size of 10% of the cyclic load range (hereafter called '10% segment size'), it may be solved partly by decreasing the segment size. However, the decrease of segment size is likely to give inaccurate compliance calculations. Using the ideal, noiseless load-displacement curves with predetermined opening load, the effects of segment size and overlapping range (increment of segment shift) were investigated in detail. It was found that the decrease of segment size and the increase of overlapping range (the reduction of increment of segment shift) are both likely to provide lower opening loads. However, the decrease of segment size is apt to induce high variability in compliance offset data as an example is shown in Fig. 5. While the standard 10% segment size provides definite crack opening loads both for the standard 5% shift and 1% shift as shown in Figs. 5a and b, the 5% segment size gives multiple crossings of the offset criterion level of 2%, indicating that the variability is very high. It can be concluded that to decrease the segment size is practically ineffective.

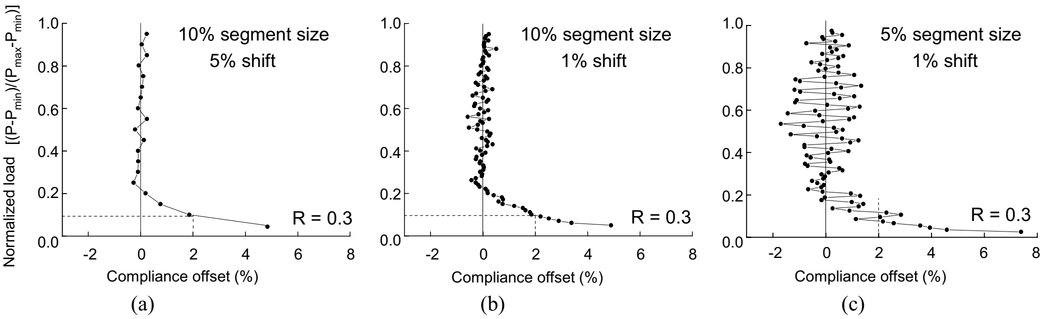


Fig. 5 Effects of segment size and overlapping range (increment of segment shift) (a) standard 5% shift for the standard 10% segment size; (b) 1% shift for the standard 10% segment size; (c) 1% shift for the 5% segment size

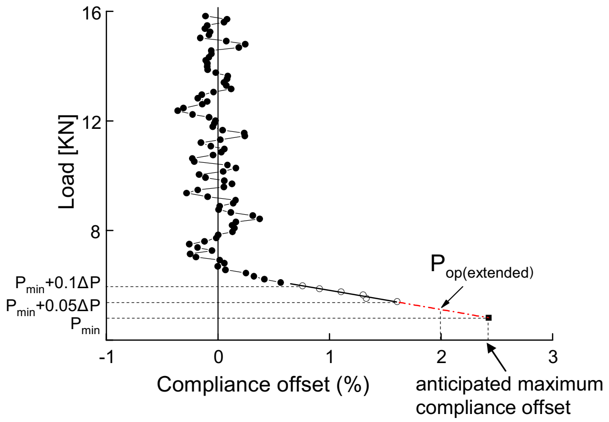
In order to solve the discontinuity problem, it was proposed to extrapolate the compliance offset data between (P_{min} + 0.05ΔP) and P_{min} (refer to Fig. 3b) where the opening load value is lack. For the purpose, compliance offset data are obtained, shifting the 10% segment size 1% by 1% (referred to as '1% shift') and a least-squares straight line is fitted to six data points between (P_{min} + 0.1ΔP) and (P_{min} + 0.05ΔP), to be extended down to P_{min}, as shown in Fig. 6a. The 2% offset criterion is applied to the extended straight line to determine the crack opening load designated hereafter by $P_{op(extended)}$. For convenience, the compliance offset at P_{min} is hereafter called 'anticipated maximum compliance offset'. Fig. 6b shows the results when the extended ASTM method (referred to as 'ext ASTM method') is applied to the data of Fig.4. The jumping behavior observed in the P_{op} – K_{max} plots and the da/dN - ΔK_{eff} plots of Fig.4 is eliminated and the data are smoothly connected.

4.2 Normalized method to solve the inconsistency problem

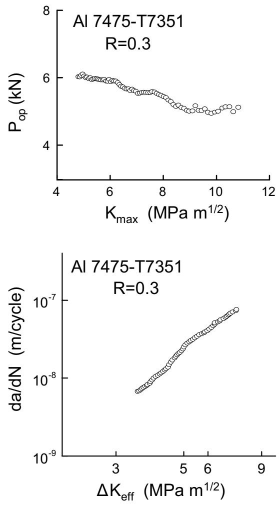
The inconsistency problem, i.e. the dependence of opening load on the maximum compliance offset value, was solved by using the concept of normalized ASTM compliance offset method (nASTM method) proposed by Song et al. [15]. The original nASTM method utilized the relative compliance offset normalized by the maximum compliance offset obtained by the original ASTM method. In the new method, instead of the maximum compliance offset obtained by the original ASTM method, the newly defined, 'anticipated maximum compliance offset' in the extended ASTM method introduced in the preceding subsection *4.1*. A new relative compliance offset is defined as

$$\text{relative compliance offset}=\frac{\text{compliance offset}}{\text{anticipated maximum compliance offset}} \tag{2}$$

Using the fatigue crack growth test data on 7474-T7351 aluminum alloy, relative compliance offset criteria of 6%, 8% and 10% were evaluated quantitatively based on the evaluation criteria introduced previously by Song et al. [16].



(a)



(b)

Fig. 6 (a) extended ASTM method; (b) an example of application of ext ASTM method

The evaluation criteria consist of the following two criteria. One is the error criterion. If the crack growth rates as a function of ΔK_{eff} are obtained for an offset criterion as schematically shown in Fig. 7, the error criterion is expressed in terms of the fraction of data falling within a scatter band of a specified factor s around the regression curves as

$$E_f(s=\sqrt{2}) = \frac{\text{number of data falling within } \frac{1}{\sqrt{2}} \le \frac{(\frac{da}{dN})_{\text{observed}}}{(\frac{da}{dN})_{\text{regression cirve}}} \le \sqrt{2}}{\text{number of total data}} \tag{3}$$

where $(da/dN)_{\text{observed}}$ and $(da/dN)_{\text{regression curve}}$ denote the observed crack growth rate and the estimated one from the regression curve, respectively. The value of $s = \sqrt{2}$ was employed for a factor of scatter band. As the error criterion cannot evaluate the correlation of da/dN versus ΔK_{eff}, the correlation coefficient r^2 is utilized as an additional evaluation criterion.

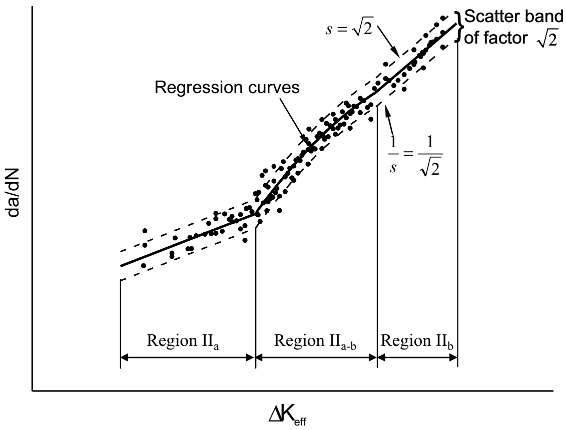


Fig. 7 Error criterion

As the correlation coefficient r^2 varies depending on the growth rate regime, the representative value of correlation coefficient r^2_{total} is calculated as

$$r_{total}^2 = \sum_{i=1}^{k} N_i r_i^2 \Bigg/ \sum_{i=1}^{k} N_i \tag{4}$$

where r_i^2 denotes the correlation coefficient for the ith growth rate regime; N_i, the number of data included in the ith growth rate regime; k is the number of growth rate regimes. Assuming for convenience that the above two evaluation criteria are equally important, the total evaluation is made using the mean value of two criteria defined as

$$\bar{E} = \frac{E_f(s = \sqrt{2}) + r_{total}^2}{2} \tag{5}$$

The closer the evaluation value is to 1, the better the method is. Generally, increasing the value of relative offset criterion reduces the data scatter, but tends to overestimate the value of ΔK_{eff}. Therefore, in determining a reasonable relative offset criterion, the precision-based (data scatter-based) evaluation is not always sufficient on its own. In addition, the evaluation should be made also in terms of accuracy, in other words, based on the mean da/dN -ΔK_{eff} relationship. Considering both the precision-based results and the accuracy-based results, finally, a relative offset criterion of 8% was employed. The method to determine the crack opening load by using the new relative compliance offset of Eq. (2) is referred to as 'the normalized-extended ASTM method' or 'n-ext ASTM method'.

5. Evaluation of the normalized-extended ASTM method

Fig. 8 shows the crack growth rates as a function of the stress intensity factor range ΔK and the effective stress intensity factor ranges ΔK_{eff} based on the standard ASTM 2% offset and the normalized-extended ASTM method for 7475-T7351 and 2024-T351 aluminum alloys. As is usually with the standard ASTM method, the growth data are somewhat widely dispersed. The normalized-extended ASTM method is found to account for the stress ratio effect very successfully. Particularly, the method improves the evaluation value based on the error criterion E_f by about 20%, in comparison with the standard ASTM method. The total evaluation value is higher for 7475-T7351 than 2024-T351 and it may be attributed to the difference in data sampling rate. The sampling rate was 1000 and 200 data pairs (load and displacement) per cycle for 7475-T7351 and 2024-T351 alloys, respectively. As the normalized-extended ASTM method is based on the so-called 1% shift of 10% segment size, the number of data pairs per cycle is very important. 300 data pairs per cycle may be a good, reasonable choice, with which 10% segment size includes more than ten data pairs and 1% shift updates more than one data pair. The sampling rate can be very easily realized by recent measuring technology.

6. Application of the normalized-extended ASTM method to random loading

Fig. 9 shows an example of load-displacement curves observed under random loading. As the fully open crack portion of a load-displacement curve varies from cycle to cycle under random loading, it is not reasonable to apply the standard or normalized extended ASTM method directly to each load-displacement curve. For example, if the ASTM method is applied to the curves C and D corresponding to the fully open and fully closed cracks, respectively, the method provides the same result, 'no closure'. In order to apply the standard or normalized extended ASTM method to random loading, a new procedure is needed to determine the reference open-crack compliance applicable to every load-displacement curve under random loading. There are two possibilities: One is to fit a least squares straight line to an upper 25% segment of the load- displacement curve corresponding to the maximum load range pair (referred to as 'the largest load cycle) of random loading and the other is, to all load-displacement curve data included within an upper 25% range of the largest load cycle in a unit random loading block during which the open-crack compliance hardly changes. The latter was found to provide more stable results because there were much more data available than for the former. The anticipated maximum compliance offset for application of the normalized extended ASTM method was determined from all load-displacement curve data included in the lowest 15% range of the largest load cycle for a unit random loading block, instead of employing only the largest load cycle. For random

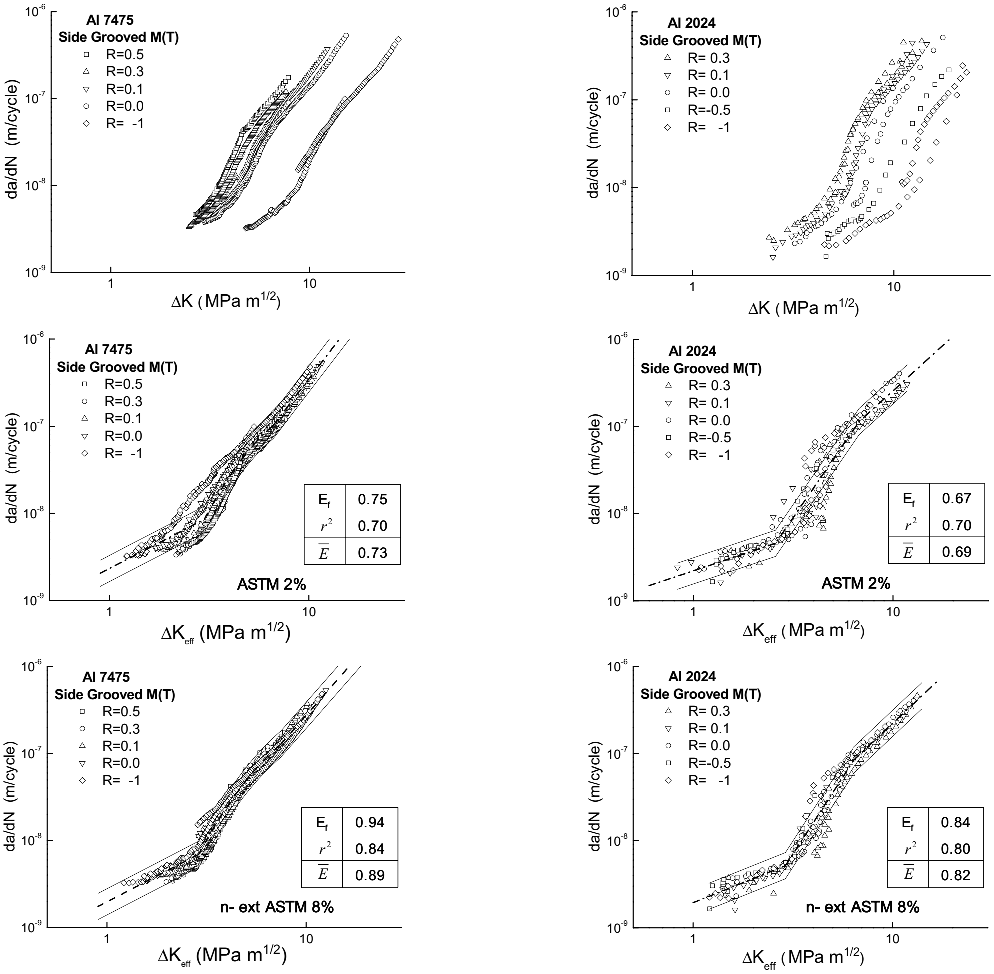


Fig. 8 Crack growth rates as a function of ΔK and ΔK_{eff}

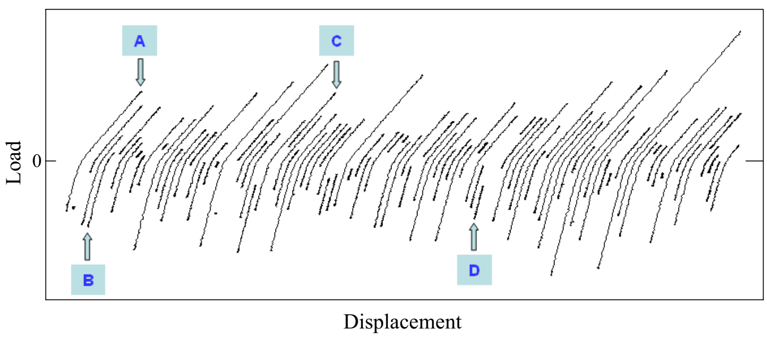


Fig. 9 Load-displacement curves observed under random loading

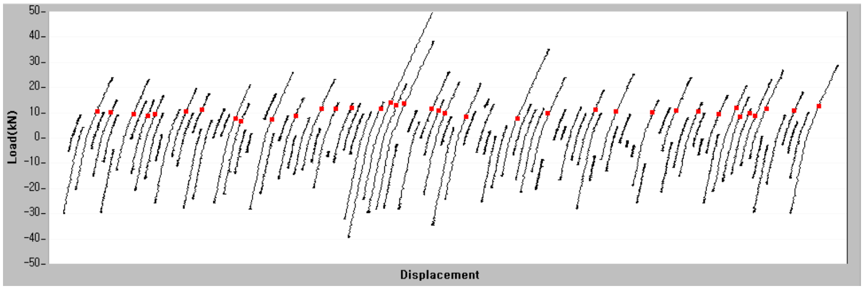


Fig. 10 Crack opening loads determined by the normalized-extended ASTM method under random loading

loading tests, narrow and wide band unit random loading blocks having history lengths of N_h =500 and 16000 were generated by computer simulation. Random loading crack growth tests were performed on 7475-T7351 aluminum alloy by repeatedly applying a unit random loading block. Examples of crack opening loads determined by the normalized-extended ASTM method during a unit random loading block are shown in Fig. 10 where the small solid points indicate the crack opening loads. Although the crack opening load could not be determined for some load cycles mainly due to high variability in compliance offset data, the crack opening load fluctuates only slightly through a random loading block. This behavior of crack opening load has been already well reported by many researchers [5, 9] who investigated crack opening behavior using the unloading elastic compliance method (the P-Δδ curve method). For convenience, the crack opening load is assumed to be nearly constant during a random loading block and the averaged one over a random loading block is employed as the representative one $K_{op\text{-}avg}$. Fig. 11 shows an example of $K_{op\text{-}avg}$ as a function of the maximum stress intensity factor of the largest load cycle K^{rp}_{max} . The crack opening load is lower under random loading than constant amplitude loading. This trend is different from the behavior of 2024-T351 aluminum alloy that the crack opening tends to be higher under random loading [9]. The results of Fig. 11 indicate that the crack closure behavior of 7475-T7351 under random loading is significant different from the behavior under constant amplitude loading and to predict the crack opening load under random loading directly from the constant amplitude loading data is very likely to lead to non-conservative crack growth predictions. As has been already well reported, the crack opening load is a function of the largest load cycle in a random load history and is hardly influenced by random load spectrum or history length.

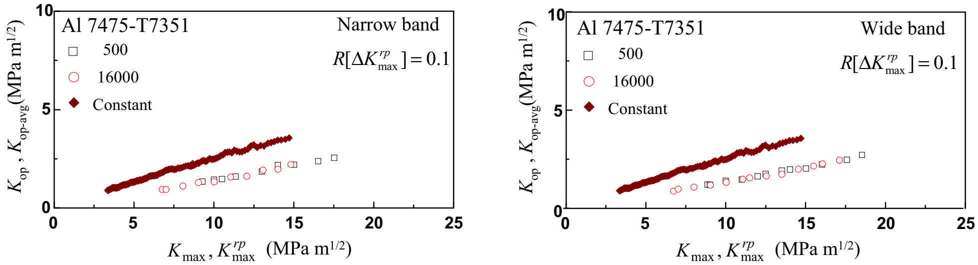


Fig. 11 Crack opening load $K_{op\text{-}avg}$ under random loading

Fatigue crack growth under random loading was predicted using the effective stress intensity factor range ΔK_{eff} based on the crack opening load determined by the normalized-extended ASTM method. The number of cycles needed for a specified crack growth increment (1.5-2.0mm), N_{pred}, is predicted and compared with the experimental one, N_{test}, as shown in Fig. 12, which shows an example of the prediction ratio N_{pred}/N_{test} plotted against K^{rp}_{max} . All the data are close to N_{pred}/N_{tes}=1, indicating that crack growth under random loading is well predicted by the effective stress intensity factor range ΔK_{eff} and the normalized-extended ASTM method is very powerful for random loading as well as constant amplitude loading.

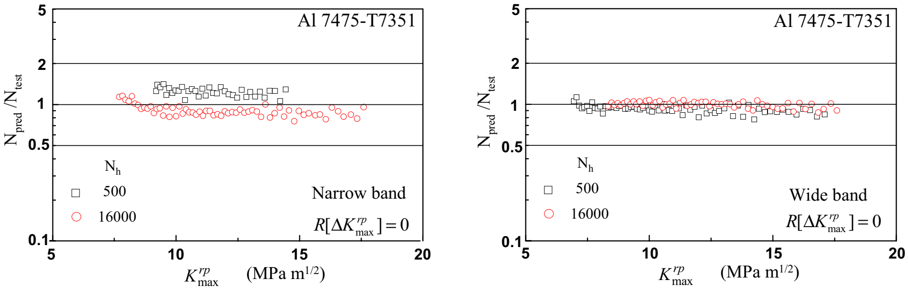


Fig. 12 Fatigue crack growth predictions based on the normalized-extended ASTM method under random loading

7. Conclusions

The normalized-extended ASTM method developed to overcome the drawbacks intrinsic to the standard ASTM method is successfully applied to random loading tests on 7475-T7351, employing a procedure relevant to random loading for estimating the reference open-crack compliance and the anticipated maximum compliance offset. The conclusions obtained are summarized as follows: 1) Crack growth under random loading can be well predicted by the effective stress intensity factor range ΔK_{eff} based on the crack opening load determined by the normalized-extended ASTM method. This indicates that the normalized-extended ASTM method is very powerful for random loading as well as constant amplitude loading. 2) The crack opening load of 7475-T7351 under random loading tends to be lower than the constant amplitude loading results, indicating that to predict the crack opening load under random loading directly from the constant amplitude loading data is very likely to lead to non-conservative crack growth predictions. This tendency is significantly different from the trend of crack opening load of other aluminium alloy 2024-T351. 3) It is strongly recommended to use the normalized-extended ASTM method.

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